

0

[illegible]3. REPORT TYPE AND DATES COVERED

~~THESIS/DISSERTATION~~

### 5. FUNDING NUMBERS

Rebecca Schultz, B.S.

AFIT Student Attending:

AFIT/CI/CIA-

University of Austin Texas

94-043

10. SPONSORING/MONITORING  
AGENCY REPORT NUMBER

DEPARTMENT OF THE AIR FORCE  
AFIT/CI  
2950 P STREET  
WRIGHT-PATTERSON AFB OH 45433-7765

**94-22532**



## 11. SUPPLEMENTARY NOTES

**DISTRIBUTION CODE**

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DTIC  
ELECTE  
JUL 21 1994

13. ABSTRACT (Maximum 200 words)

DTIC QUALITY INSPECTED 8

15. NUMBER OF PAGES

16. PRICE CODE

20. LIMITATION OF ABSTRACT

94-002

**CHARACTERIZATION OF THE FAST-PHASE  
COMPONENT OF THE VESTIBULO-OCULAR  
RESPONSE**

by

**REBECCA SCHULTZ, B.S.**

**THESIS**

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

**MASTER OF SCIENCE IN ENGINEERING**

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CHARACTERIZATION OF THE FAST-PHASE  
COMPONENT OF THE VESTIBULO-OCULAR  
RESPONSE

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## **Acknowledgements**

I would like to thank Dr. Edward Engelken and other members of the Otolaryngology Function, Clinical Sciences Division, Aerospace Medicine Directorate, Armstrong Laboratory, Brooks AFB, Texas for the use of their equipment and expertise.

April 11, 1994

# **CHARACTERIZATION OF THE FAST-PHASE COMPONENT OF THE VESTIBULO-OCULAR RESPONSE**

Rebecca Schultz, Master of Science in Engineering  
The University of Texas at Austin, 1994

Supervisor: H. Grady Rylander, III

The vestibular system can be tested by recording eye-movement responses to whole-body angular acceleration. The resulting vestibulo-ocular reflex (VOR) has two components. The slow-phase component is a compensating movement in the same direction as the stimulus, while the fast-phase component is a refixation movement usually in the opposite direction of the stimulus. The slow-phase signal is extracted and evaluated to determine the condition of the vestibular system. Currently the fast-phase component is not used for diagnostic purposes. Normal subjects were tested and the extracted fast-phase signal was characterized using parameters such as amplitude, velocity and duration of each fast eye movement.

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## **Chapter One: Introduction**

Our senses are continuously collecting information about the outside world. The nervous system relays this information to the brain where it is used to make decisions on how the body should react. The most well known senses are touch, sight, hearing, smell and taste. People consciously use their hands, eyes, ears, nose and tongue every day to help assess what is happening in the world around them.

A much less prominent, although crucial, sense is that of balance. It is unconsciously used to coordinate body movement, posture and eye movements. For proper balance, continuous information is needed on body, head and eye position. The sources of this information must be independent, since each can move in relation to the others. Information used to determine body position is gathered through the somatic sensory system. Somatic receptors are located throughout the body and include touch, pain, thermal sensations, and proprioception (which measures mechanical displacement of muscles and joints). For head position and movement, the vestibular system is the primary collector of information. The oculomotor system controls eye movement and position. The vestibular and oculomotor systems communicate with each

other to track how the head and eyes are moving through space relative to each other. These systems also work together to keep visual images stable and centered on the fovea.

When head and eye position are not correctly perceived and transmitted to the brain, the overall functioning of the body is disrupted. Severe dizziness and nausea can result. These symptoms can be very frustrating and the cause difficult to diagnose. A series of vestibular function tests can be given to try to pinpoint where the problem is occurring. One of the more common tests uses sinusoidal harmonic acceleration, where patient eye position is recorded during head rotation. The rotation elicits a physiological response called a nystagmus. The nystagmus is made up of two components: a slow movement as the eye moves in response to the vestibular input, and a quick movement as the eye jumps back towards the center. Currently only the slow-phase velocity, which is filtered from the eye movements, is used to diagnose abnormalities. This thesis characterizes the fast-phase movements in normal patients. Fast-phase movements are readily available from current testing procedures and may offer another avenue for diagnosing dizzy patients.

The next chapter reviews the physiological systems involved in vestibular function testing. These systems must be

understood so that detected abnormalities can be traced back to their origin. The third chapter describes the sinusoidal harmonic acceleration test and the set up used to collect data for this thesis. The results are given in the fourth chapter. Chapter five discusses current literature on fast phase movements.

## **Chapter Two: Background**

### **PHYSIOLOGY OF THE VESTIBULAR SYSTEM**

The vestibular apparatus is located in the inner ear, or labyrinth. It consists of the otolith organs and three mutually perpendicular semicircular canals. The otolith organs, which include the utricle and saccule, detect linear acceleration from head movement and are responsible for determining the position of the head with respect to gravity. The semicircular canals detect angular acceleration, each in a different direction. As the head is rotated, endolymph fluid moves through the canals causing the displacement of sensory hairs located at the end of the canals, in an area called the ampulla. The distance the hairs are displaced and the direction of the displacement affects the electrical activity of the nerve fibers coming from the receptor cells. When a hair cell is bent in one direction, along its axis of polarity, there is an increase in the firing rate of the corresponding nerve. When the hair is bent in the opposite direction, there is a decrease in the firing rate of the corresponding nerve. When the head turns to the right, the hair cells in the right ear are bent along their axis of polarity causing an excitation or increase in the firing rate of that nerve. The hair cells in the left ear are bent against their axis of

polarity decreasing, or inhibiting, the firing rate of the nerve. In this manner the brain perceives the turning motion due to an excitation in one ear and an inhibition in the other.

### THE OCULOMOTOR SYSTEM

Information collected by the vestibular system on head movement is relayed to the oculomotor system so that the eyes can be moved in a compensatory direction and speed. Three pairs of muscles control eye movements in each eye, each pair acting with complimentary action, as shown in Figure 1. The medial and lateral recti move the eye toward the nose, adduction, and away from the nose, abduction, respectively. Each of the remaining four muscles move the eye around two axes. One of these axes runs straight into the eye along the line of sight. The top of the cornea rotates towards the nose for intorsion and away from the nose for extorsion. The second axis runs from temple to temple. The eye rotates up for elevation and down for depression. The inferior and superior recti work as a pair to cause depression-extorsion and elevation-intorsion, respectively. While the superior and inferior obliques cause depression-intorsion and elevation-extorsion, respectively.

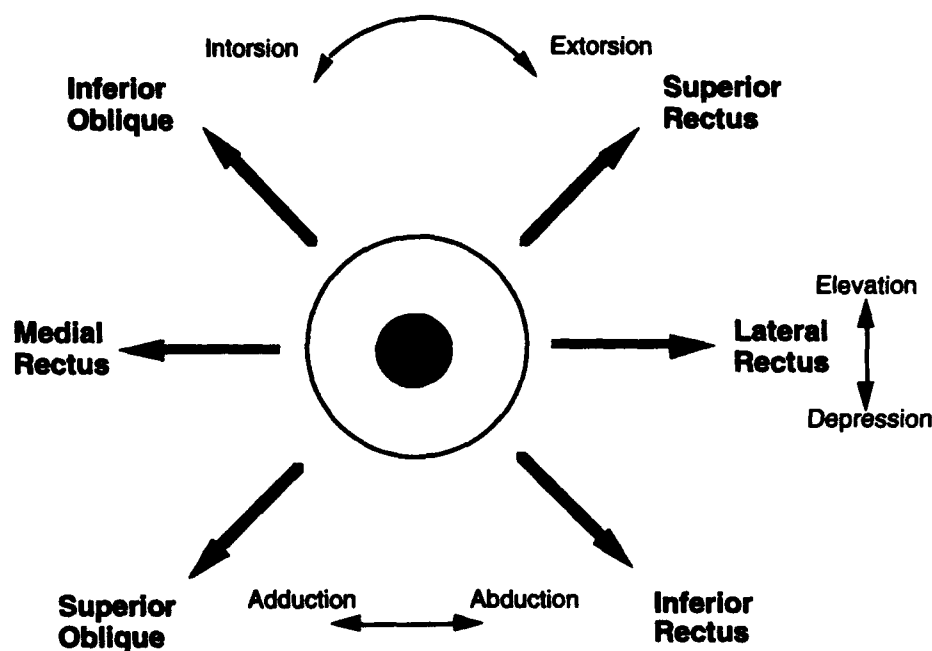


Figure 1. Schematic of left eye showing muscles and axes of rotation and principal actions of the muscles.

These six muscles work together to move the eyes in five different movements. Three of the movements, saccadic, smooth pursuit and vergence, adjust the eye to keep a visual target on the fovea. Saccadic eye movements shift the fovea rapidly to a target (not necessarily visual) on the periphery. There is usually one large saccade, followed by several smaller saccades to adjust eyes on the target. Smooth pursuit is used to follow a moving target. There must be a visual target, otherwise the eyes will move in small jumps instead of a

smooth movement. For vergence each eye moves differently to focus on targets at different depths of view. This is the only movement in which the eyes are not moving together.

Two other eye movements, vestibulo-ocular and optokinetic, are used to stabilize the eye during head movement. These are the eye movements that are studied in this thesis. Vestibulo-ocular movements are involuntary movements that hold an image stable on the retina during brief or rapid head movements. The semicircular canals in the ear signal the speed and direction of head rotation. The oculomotor system then rotates the eyes in an equal and opposite direction. Optokinetic movements use visual information to drive eye movements. They are used during slow and sustained movements when the short latency and slow decay of the vestibular system impairs the vestibulo-ocular movements.

During head rotation or visual field rotation, the eyes move in a pattern called nystagmus. There is vestibular nystagmus and optokinetic nystagmus, depending on the origin of stimulation. Nystagmus can be broken into two components: a slow-phase and a fast-phase. The slow-phase movement is similar to smooth pursuit movements. The eyes, initiated by impulses from the labyrinths, slowly rotate to the outer edge of



their orbit. When the limit of movement is reached, the eyes quickly snap back towards center line and a new fixation point. This fast-phase portion of the nystagmus is similar to saccadic movements and is triggered by a center in the brain stem.

### **VESTIBULAR CONTROL OF THE OCULOMOTOR SYSTEM**

The best understood pathway for extraocular motor control is that of the vestibulo-ocular response (VOR), as diagrammed in Figure 2. Control of the extraocular muscles for the vestibular nystagmus originates in the semicircular canals. Nerves from the receptor cells in the semicircular canals and otolith organs join together to form the vestibular portion of the eighth cranial nerve. The eighth nerve runs through the cerebellopontine angle to the lateral aspect of the pons, to the vestibular nuclei located in the medulla. From the vestibular nuclei connections are made to the cerebellum via the juxtarestiform body, the spinal cord forming the vestibulospinal tract and other areas throughout the brainstem, including the motor neurons of the extraocular muscles, through the crossed and uncrossed fibers of the medial longitudinal fasciculus (MLF). Excitatory and inhibitory signals are sent to complementary muscles in both eyes.

There are three nuclei that contain the motor neurons for the six oculomotor muscles. The abducens nucleus is located in the pons, in the floor of the fourth ventricle. It innervates the lateral rectus. Located in the midbrain at the level of the superior colliculus is the oculomotor nucleus, innervating the medial, inferior and superior recti and the inferior oblique muscles. The superior oblique muscle is innervated by the trochlear nucleus located in the midbrain at the level of the inferior colliculus.

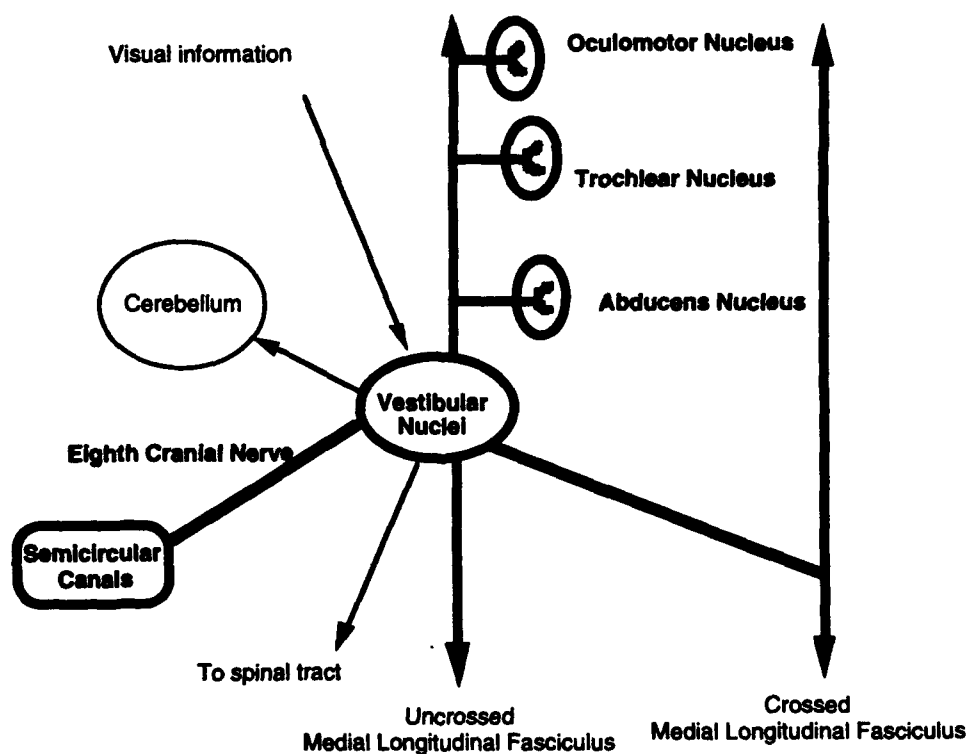


Figure 2. Pathways of the vestibular system.

Visual information is used for the optokinetic nystagmus (OK). Motion of objects is detected in the striate cortex, medial temporal, and medial superior temporal areas of the brain. Output from these areas is directed to the dorsolateral pons and cerebellar flocculus where the velocity of the visual target is computed. This information is then sent to the pontine gaze center and to the oculomotor neurons that control eye movement to compensate for the moving target.<sup>1</sup>

#### **PATHOLOGIES OF THE VESTIBULAR / OCULOMOTOR SYSTEMS**

There are many disorders that affect the vestibular and oculomotor systems. These disorders can be classified as peripheral or central with the dividing point being where the eighth cranial nerve enters the brainstem. Peripheral diseases affect the labyrinths and eighth nerve, and often also affect hearing. Such disorders include Meniere's disease, which is caused by an overproduction of endolymph, toxic drugs such as streptomycin and gentamycin, acoustic neuroma, temporal bone injuries, syphilis, multiple sclerosis, and viral labyrinthitis

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<sup>1</sup>Eric Kandal, James Schwartz, and Thomas Jessell, *Principles of Neural Science*, (Connecticut: Appleton & Lange, Norwalk, 1991), 673.

resulting from rubella, mumps and measles.<sup>2</sup> Central disorders include lesions in any area of the brain that is involved in vestibular and oculomotor processing, including the brain stem, vestibulo-cerebellum, parietal lobe and magnocellular layers of the lateral geniculate nucleus, striate cortex, middle temporal area and medial superior temporal area.

### VESTIBULAR FUNCTION TESTS

When a patient exhibits symptoms of a vestibular disorder, like nausea and dizziness, a series of vestibular function tests<sup>3</sup> are often used to help identify the site of a lesion or abnormality. These tests use different combinations of stimuli to elicit a nystagmus response, which is recorded and analyzed. An increased, decreased or abnormal nystagmus response can be associated with ocular, vestibular and central nervous system diseases. By looking at all of the tests together, including which ones are normal and which ones are abnormal, the source of the problem can sometimes be identified. Further testing in that particular area may be undertaken to confirm the diagnosis.

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<sup>2</sup>Larry J. Bradford, ed., *Physiological Measures of the Audio-Vestibular System*, (New York: Academic Press, 1975), 23.

<sup>3</sup>Working Group on Evaluation of Tests for Vestibular Function, "Evaluation of Tests for Vestibular Function", *Aviation, Space and Environmental Medicine*, (February 1992), A3.

One of the first tests in the vestibular function test series is usually the saccade test, which determines how well the patient makes quick jumps to new targets. A small light is turned on in the center of the subjects visual field. As it is turned off, a light in the periphery, usually horizontally, but sometimes vertically, is turned on. The patients eyes are tracked as the patient follows a random series of jumps. The amplitude and velocity of the jump, the time delay between start of jump, asymmetry and overshoot or undershoot are all measured in each eye for evaluation. Abnormalities will indicate problems in the visual or oculomotor systems.

In normal subjects, nystagmus is not present when looking straight ahead or at a fixed position to the periphery. The only exception is possibly for extreme angles. The spontaneous and gaze evoked nystagmus test is used to look for the presence of nystagmus without vestibular stimuli. The subject fixates on real or imagined targets at various positions and the presence of nystagmus is noted. Gaze or positional nystagmus indicates a peripheral vestibular or central nervous system abnormality.

Smooth pursuit is tested with the ocular pursuit test. The subject follows a small target as it moves in a periodic, horizontal motion. How well the subject tracks the object to

either side and at different velocities is recorded. Abnormalities in this test often indicate a central nervous system problem, either in visual processing centers of the brain or the oculomotor system.

Changes in a subject's orientation with respect to gravity may cause a positional nystagmus. Moving the subjects head and holding it in the new position such that the orientation of the semicircular canals is affected allows for the static and dynamic testing of vestibular function. Normal subjects will show compensatory eye movements during positioning, but they should stop soon after the new position is reached. If nystagmus continues, it may indicate an abnormality.

Another test that induces nystagmus by vestibular stimulation is the caloric test. By putting water that is either warmer or colder than body temperature into the ear, the lateral semicircular canals can be either excited or inhibited in each ear, independently. The heat transfer resulting from the temperature gradient between the water and the inner ear causes a density gradient in the endolymph, triggering the hair cells and resulting in a nystagmus. The subject has a sensation of spinning and may experience nausea and vomiting. The slow component of the resulting nystagmus can be evaluated by finding its slope, giving the slow component velocity. Since

responses vary greatly between subjects, it is often most useful to compare the response to excitation versus inhibition and right ear versus left ear. This test does not evaluate ocular responses, just vestibular responses. Abnormalities in the vestibular nystagmus could indicate peripheral vestibular lesions, or central lesions localized in the vestibular nuclei.

A relatively new test rotates the subject about the vertical axis with a sinusoidal angular acceleration. This motion closely imitates natural stimulation of the vestibular system. An advantage to this test is that both the right and the left labyrinths receive a controlled stimulus, one side excitatory and the other side inhibitory. By rotating the subject in the dark, a purely vestibular response, VOR, is elicited. A visual response, OK, can be obtained by rotating stripes, in the same sinusoidal rotation, around a stationary subject. These two stimuli can be combined by rotating the subject with the stripes stationary to get a visual vestibulo-ocular response, VVOR. For each of these situations the slow component of the nystagmus is evaluated. Looking at which tests are normal and which are abnormal can help locate a lesion. For example, brainstem lesions are thought to affect visually and vestibularly evoked reflexes, while vestibulo-cerebellum and parietal lobe lesions affect visual but not vestibular evoked

responses.<sup>4</sup> This thesis uses the rotational angular acceleration test to record vestibulo-ocular, optokinetic and visual vestibulo-ocular nystagmus.

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<sup>4</sup>Working Group on Evaluation of Tests for Vestibular Function, A12.



## Chapter Three: Method

For the results presented in this thesis, fourteen subjects with no physical complaints underwent rotational testing. Their ages ranged from 20 to 53 years, with a mean age of 30.8 years.

During testing, eye movements were recorded using a standard electrooculographic (EOG) system with a bandwidth .05 Hz to 30 Hz. The eye, with a working retina, has a standing potential between the cornea and posterior of the eye, as shown in Figure 3. Electrodes placed around the orbit of the eye can measure the direction of gaze with respect to the head. Within the limits of  $\pm 45$  degrees, there is a linear relationship between the gaze angle,  $\theta$  in radians, and the measured electrode voltage  $e$ , in millivolts:

$$e = E \theta,$$

where the proportionality constant,  $E$  is typically 0.600 millivolts.<sup>5</sup> Temple electrodes were placed on the outer canthi of each eye, aligned with the center of the pupil, so that horizontal eye movements could be recorded, as shown in Figure 4. Ground electrodes were placed on the bridge of the nose.

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<sup>5</sup>L.A. Geddes and L.E. Baker, *Principles of Applied Biomedical Instrumentation*, (New York: John Wiley & Sons, 1989), 766.

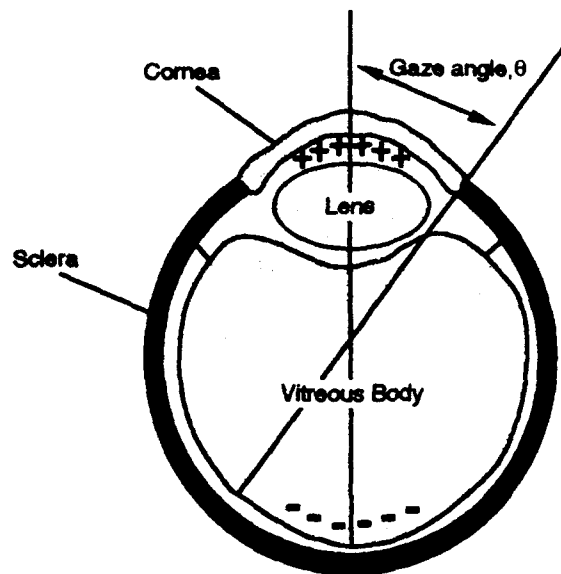


Figure 3. The standing potential of the eye.

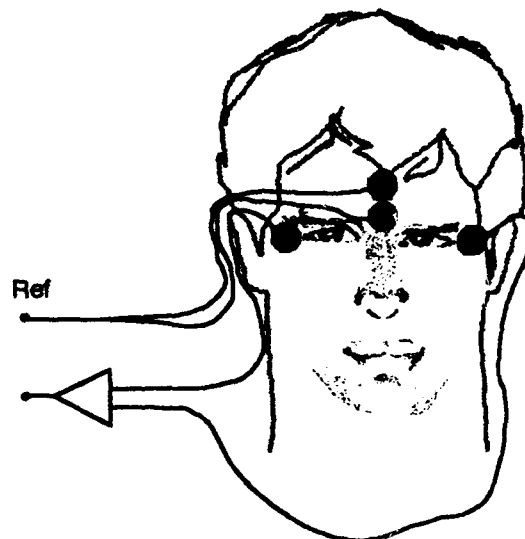


Figure 4. Electrode placement.

Each subject was seated on a chair in the middle of a circular chamber. Each subject's head was secured to the chair back so that the movement of the chair and head would be the same. All subjects underwent three tests, a vestibular response test, an optokinetic response test, and a combined test. For each subject the vestibular test was done first, then the optokinetic, then the combined. Since the vestibular test is done without the subject fixating on any object, each subject was placed in total darkness. The EOG changes with varying illumination, but this change is not immediate. Therefore, before testing began each subject was dark adapted for 15 minutes, assuring a nonvarying EOG reading.

Two stimuli were applied to each subject, a rotational stimuli to elicit a vestibular response and a optokinetic stimuli to elicit a visual response. For the vestibular stimuli, pure sine waves drove a servo-controlled torque motor system mounted to each subject's chair to produce whole-body angular acceleration about a vertical axis. The equation of the rotational stimulus is,<sup>6</sup>

$$\dot{\theta}(t) = A \sin(2\pi ft).$$

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<sup>6</sup>Conrad Wall, "The Sinusoidal Harmonic Acceleration Rotary Chair Test: Theoretical and Clinical Basis", *Neurologic Clinics*, (1990; Vol. 8, No 2), 270.

The peak velocity,  $A$ , was 60 deg/sec and the frequency,  $f$ , was 0.05 Hz. This frequency was chosen because it is known to produce a vigorous reflex response without discomfort to each subject.<sup>7</sup> Each subject was rotated in this manner in the dark to elicit a VOR. For the optokinetic test, stimuli were vertical, alternating black and white stripes that were projected onto the walls of the chamber. The same equation of rotational stimulus applies with the lines rotating at a peak velocity of 60 deg/sec and frequency of 0.05 Hz with each subject stationary to elicit a purely OK response. For the combined VVOR test, the lines were stationary and each subject rotated. Each test was for 200 seconds, although only 100 seconds (5 complete cycles) of data were actually used for the analysis.

The combined eye position was measured across the two temple electrodes at a sampling frequency of 128 Hz and saved to a computer. This eye position data was filtered using three filters developed, tested, and currently used at Brooks AFB.<sup>8</sup> The first filter, a nonlinear order-statistic filter called a predictive Finite Impulse Response (FIR) Median Hybrid, was used to smooth the eye position data. It used a piecewise

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<sup>7</sup>Working Group on Evaluation of Tests for Vestibular Function, A12.

<sup>8</sup>Edward Engelken, Kenneth Stevens, Ann Bell, and John Enderle, "Linear Systems Analysis of the Vestibulo-Ocular Reflex: Clinical Applications", *Biomedical Sciences Instrumentation*, (1993; Vol 29), 320.

continuous second-order polynomial as a root signal. Characteristics in the nystagmus data that were consistent with the root signal, like the ramp-like slow- and fast-phases and the sharp transitions between slow- and fast-phases were preserved. Characteristics that were not consistent with the root signal, like oscillations and impulses were attenuated.<sup>9</sup>

A band-limited differentiating filter was used next to find the eye velocity data. In particular, a linear FIR band-limited filter with a cutoff frequency of 30 Hz was used.<sup>10</sup> The filtered eye position data is shown in Figure 5.

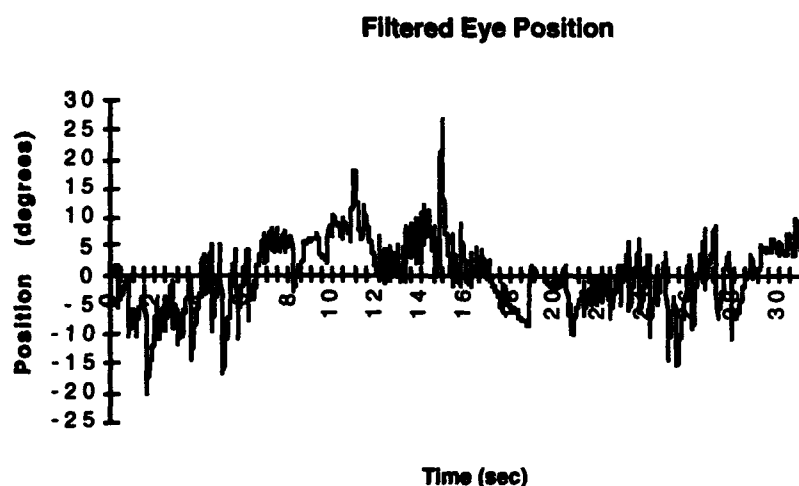


Figure 5. Filtered eye position data.

<sup>9</sup> Edward Engelken and Kenneth Stevens, "A New Approach to the Analysis of Nystagmus: An Application for Order-Statistic Filters", *Aviat, Space, Environ. Med.*, (1990), 860.

<sup>10</sup> Engelken, "A New Approach ... ", 860.

The eye velocity data, shown in Figure 6, contains the slow-phase velocity (SPV), a sinusoidal pattern approximately 180 degrees out of phase with the head movement, with intermittent fast-phase velocity (FPV) spikes. In order for each component to be analyzed, the SPV and FPV signals must be separated. The third filter, an adaptive asymmetrically trimmed-mean (AATM) filter<sup>11</sup>, is a nonlinear order statistic filter. It separated the SPV and FPV by assuming in any 1 second window a majority of the points are part of the SPV. A sliding window was moved across the velocity data, at each point a histogram was taken, and the average of the dominant mode was taken as the SPV.

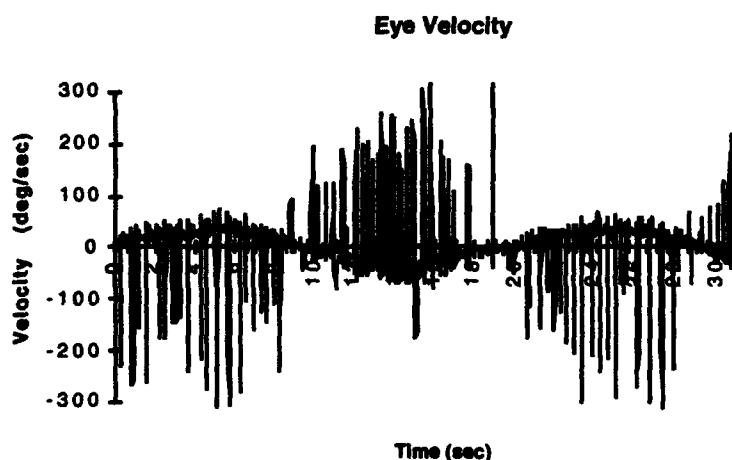


Figure 6. Eye velocity data.

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<sup>11</sup>Engelken, "A New Approach ...", 860.

The SPV, and FPV (found by subtracting the SPV from the total eye velocity) were then analyzed using programs written in LABVIEW, a data acquisition and analysis software program. Standard parameters used to describe the SPV are gain, phase and asymmetry. In order to find the gain and phase, the transfer function of the VOR must be found. The head velocity (turntable velocity) is the input (x) to the system, and the SPV is the output (y) of the system. The transfer function can be defined as:

$$H(f_s) = \frac{G_{xy}(f_s)}{G_x(f_s)}$$

where  $f_s$  is the frequency of the stimulus (0.05),  $G_x(f_s)$  is the auto-spectral density function of the input, and  $G_{xy}(f_s)$  is the cross-spectral density function.<sup>12</sup> Using the cross-spectral density function instead of just the output auto-spectral density function reduces the noise of the system. The input oscillates symmetrically around zero, therefore the output should also. The symmetry of the VOR is described by comparing the amount of right-going eye movements to left-going eye movements. This is defined as:

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<sup>12</sup>Engelken, "Linear Systems Analysis ...", 320.

$$ASYM(f_s) = \frac{\sum |SPV_{RT}| - \sum |SPV_{LT}|}{\sum |SPV_{RT}| + \sum |SPV_{LT}|} \times 100\%$$

where  $|SPV_{RT}|$  and  $|SPV_{LT}|$  are the magnitudes of the right-going and left-going SPV, respectively.<sup>13</sup>  $ASYM = 0$  indicates a symmetrical output, while  $ASYM > 0$  indicates a dominance towards the right and  $ASYM < 0$  indicates a dominance towards the left.

An extensive analysis of the fast-phase component has not been previously reported, and this thesis presents a characterization of a normal fast-phase beat. The flow of the program written in LABVIEW, for the analysis of the FPV, is shown in Figure 7. Each fast-phase beat was found using a zero cross detector and analyzed to determine its direction, peak velocity, amplitude, duration and time since the start of the previous fast-phase beat. Basic statistics and histograms were compiled in Statview, a statistical analysis software program, for each characteristic.

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<sup>13</sup>Engelken, "Linear Systems Analysis ...", 321.



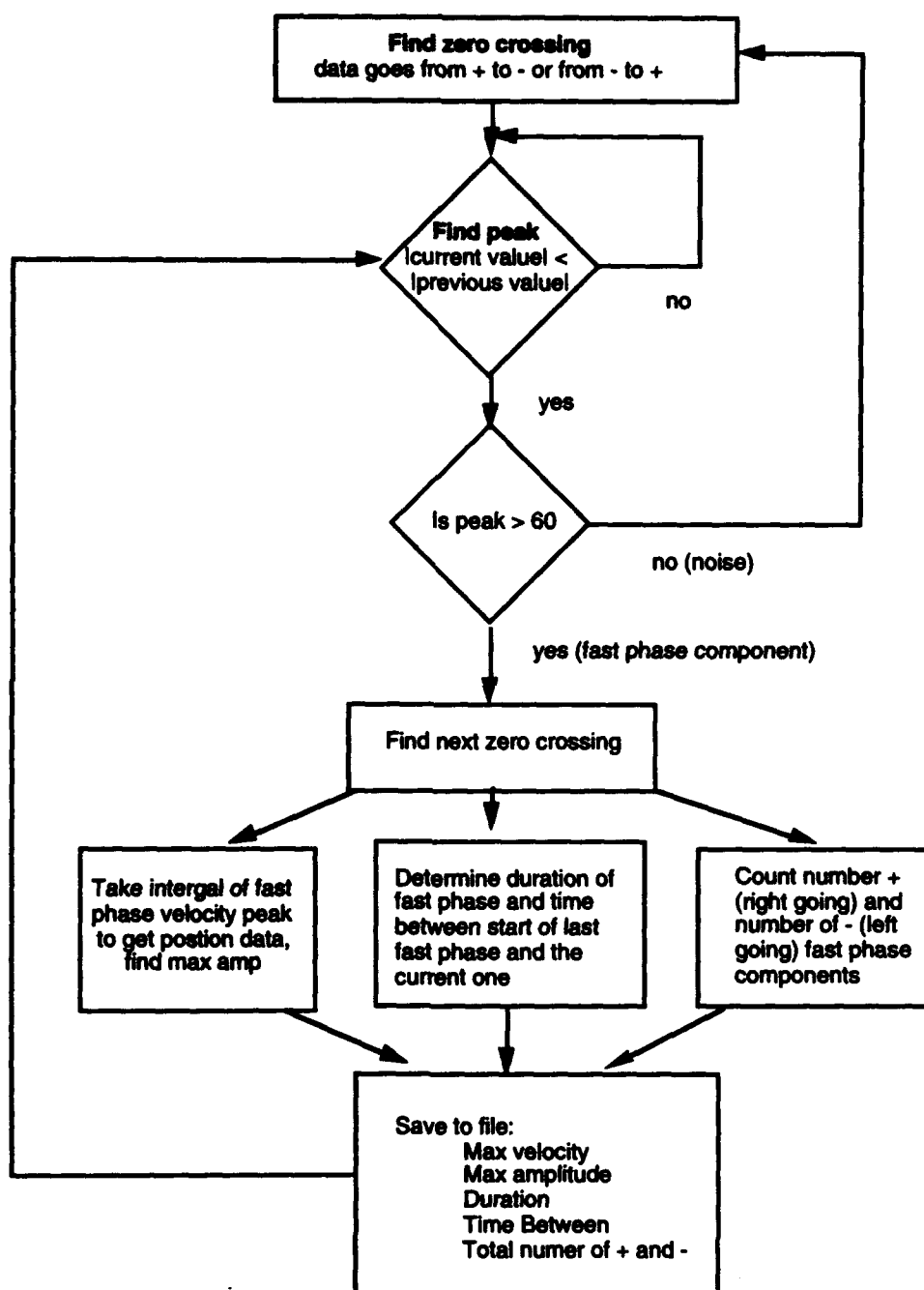


Figure 7. Flow graph of fast-phase analysis program.

## **Chapter Four: Results**

A total of fourteen subjects underwent rotational testing, 10 males and 4 females. One of the male subjects was found to have abnormal slow-phase results. A subsequent CAT scan indicated that a blow to the head during an accident a few weeks before was the cause of the abnormal slow-phase responses. This subject's responses are not included with the normal responses, but are tabulated separately.

An example of a typical subject's data when using both vestibular and visual stimuli, is given in Figures 8, 9, 10 and 11. The subject for these figures is a 26-year-old female. Figure 8 is a graph from the slow-phase analysis program in LABVIEW. Figure 9 shows the results of the fast-phase analysis program in LABVIEW. The statistical analysis of this data, calculated using Statview, is shown in Figures 10 and 11. Figure 10 shows histograms for amplitude and peak velocity of the right-beating and left-beating fast-phase movements. Histograms of the duration of each fast-phase and the time between fast-phases are shown in Figure 11.

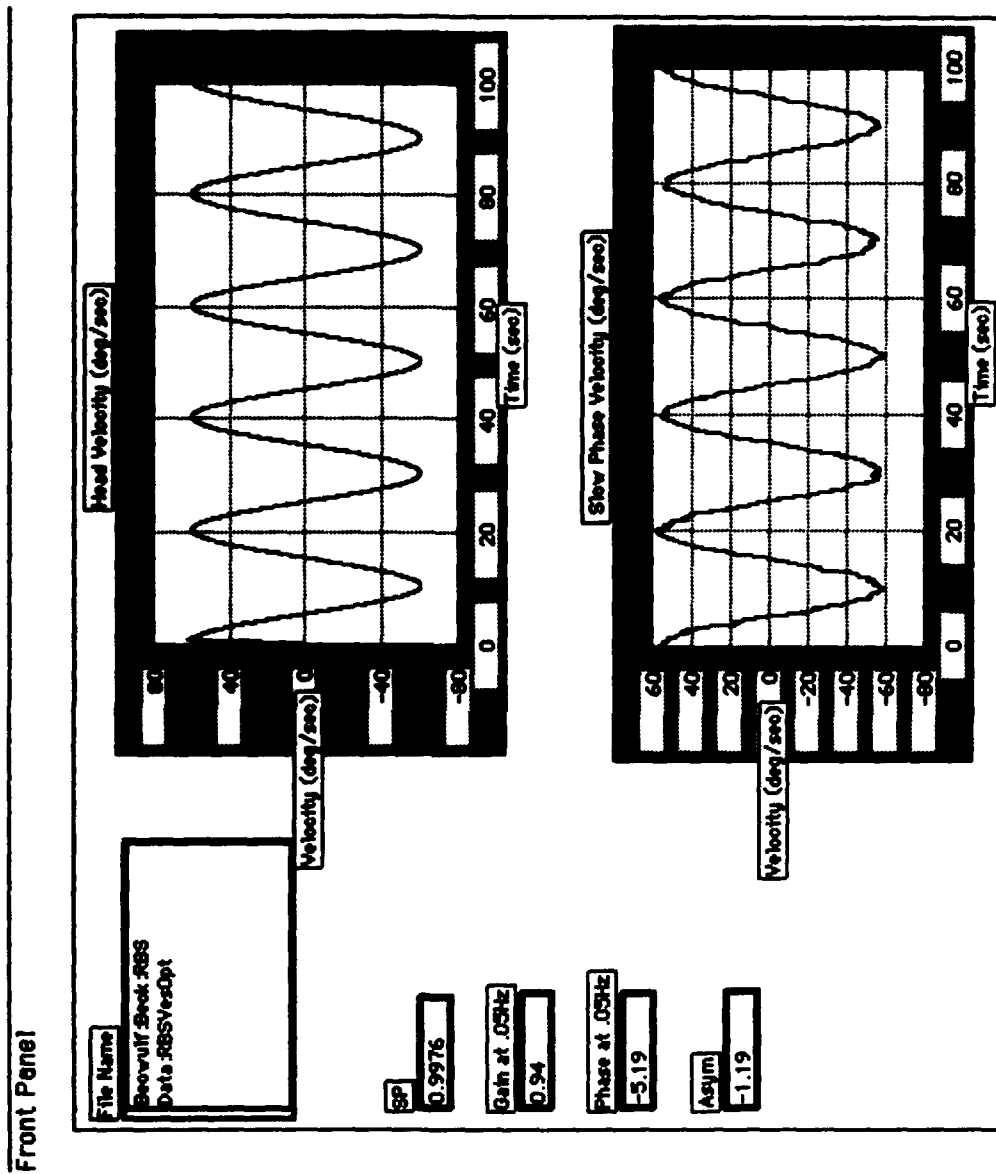


Figure 8. Slow-phase analysis.

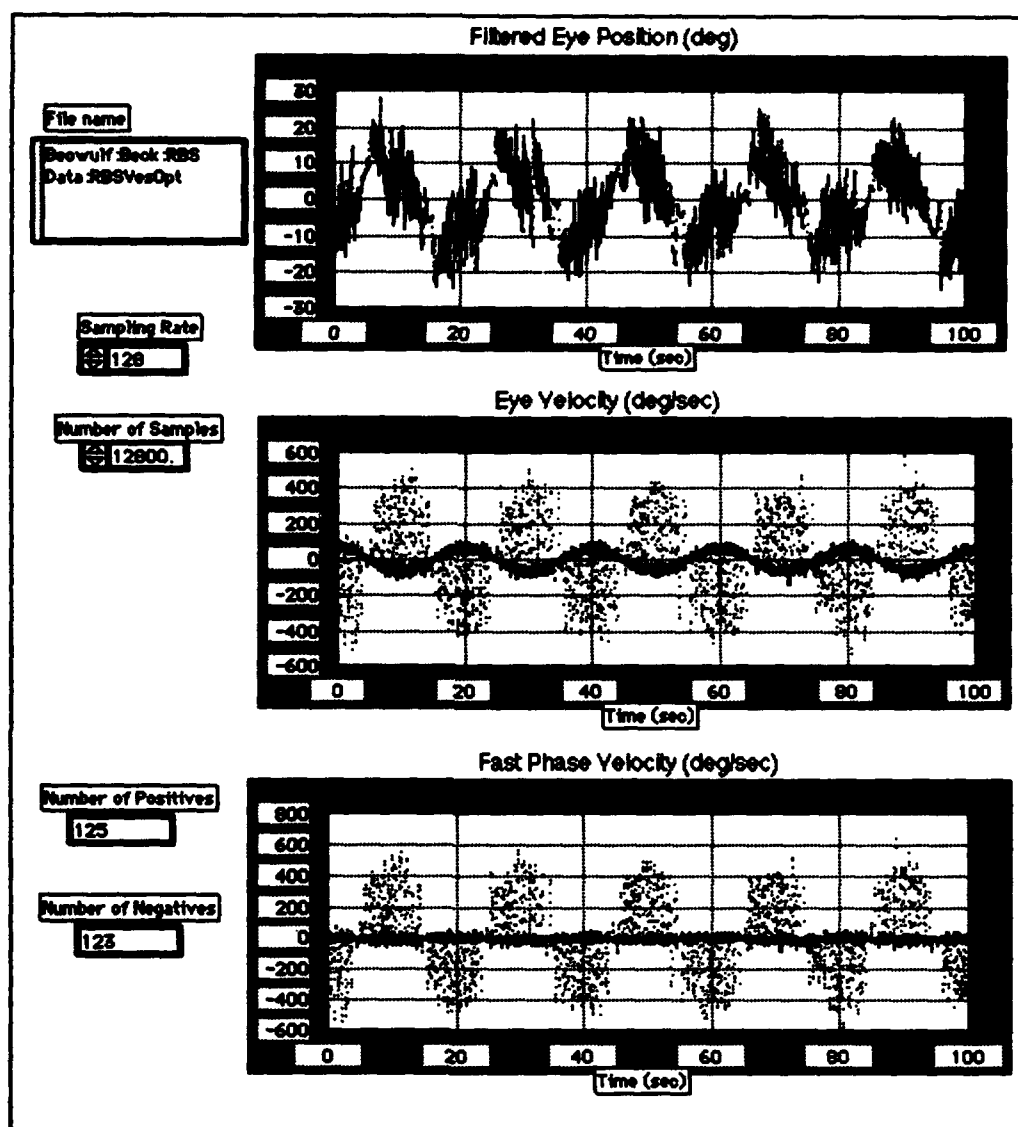


Figure 9. Fast-phase analysis.

## RBS Optokinetic/Vestibular Response

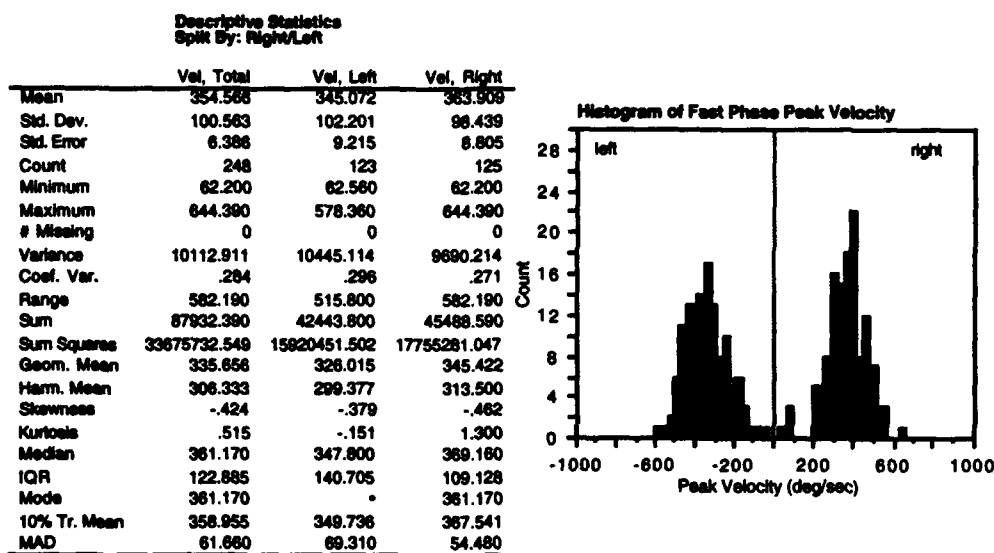
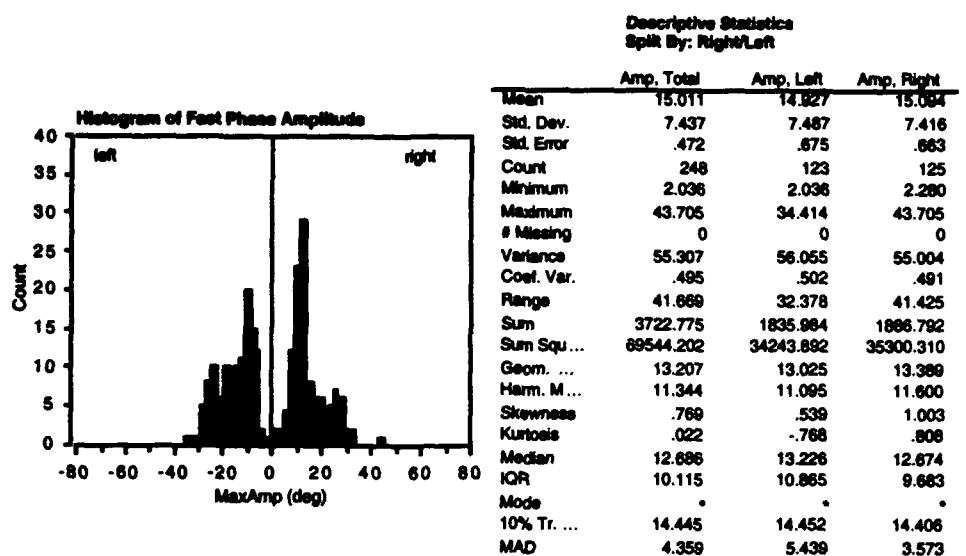


Figure 10. Amplitude and peak velocity histograms.

## RBS Optokinetic/Vestibular Response

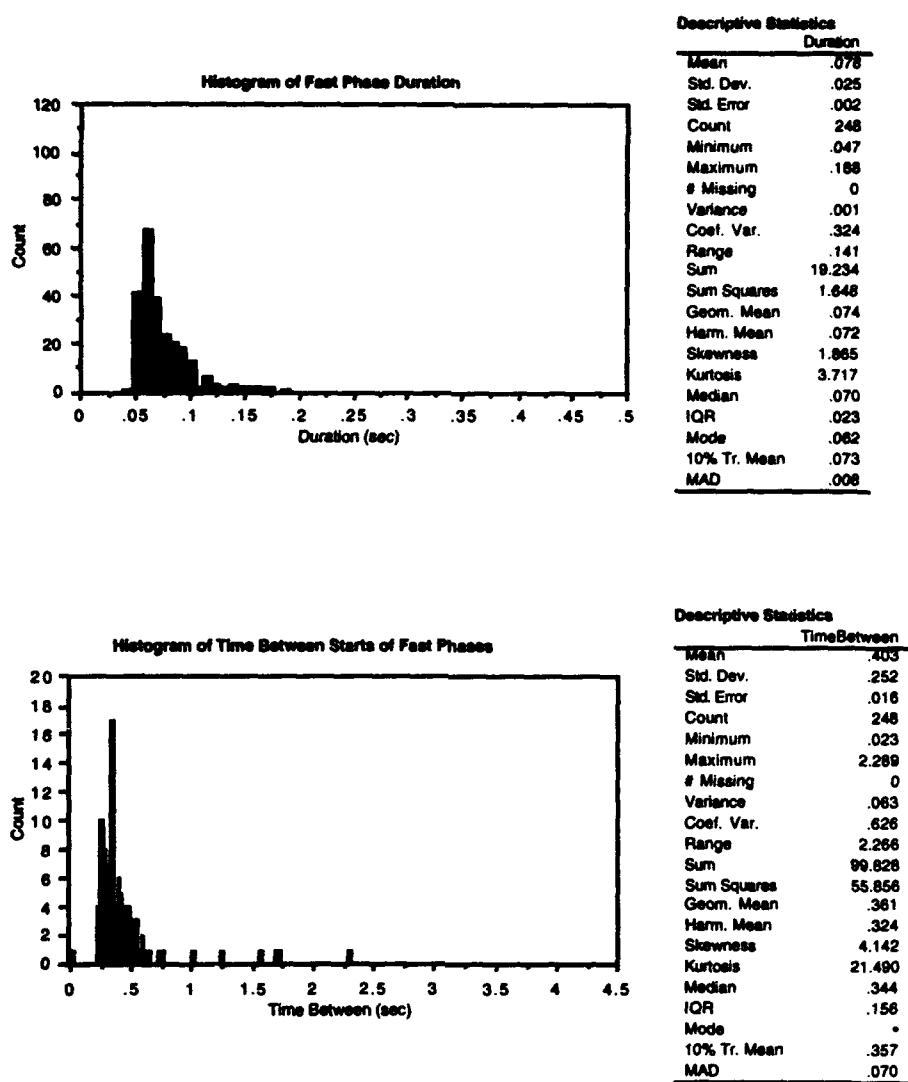


Figure 11. Duration and time between histograms.

The average of the thirteen normal subject's slow-phase results are shown in Table 1. These means are similar to the findings of other authors for normal subjects.<sup>14,15</sup>

Table 1. Summary of slow-phase analysis.

	VOR	OK	VVOR
Gain	0.66±0.11	0.84±0.15	0.95±0.04
Phase	11.3±3.8	1.7±4.3	5.2±0.8
Asymmetry	-7.0±11.2	0.9±6.0	-0.2±2.3

Mean±standard deviation, Phase in deg

The fast-phase responses include both right-moving and left-moving beats. For the analysis in this thesis, each direction is considered a different case. In a normal subject there should be little difference between right- and left-moving beats. Table 2 summarizes the mean ratios of right-moving to left-moving beats in terms of amplitude, peak velocity and total number. If a subject has a ratio that is greatly different than one, this may indicate that something is wrong in either the right or left conjugate gaze pathway.

<sup>14</sup> Engelken, "Linear Systems Analysis ...", 322.

<sup>15</sup> Working Group on Evaluation of Tests for Vestibular Function, A12.

Table 2. Summary of right to left fast-phase ratios.

Right/Left Ratio...	VOR	OK	VVOR
Amplitude	1.07±0.15	1.00±0.11	0.97±0.06
Velocity	1.03±0.11	0.98±0.10	01.00±0.08
Total Number	1.08±0.06	1.01±0.09	1.02±0.06

Mean±standard deviation

Table 3 summarizes the averages, for all subjects, of the fast-phase characteristics for each test condition, VOR, OK, VVOR. The average amplitude is the mean of all fast-phase beats, moving in one direction, measured over the course of the 100 second test. The average peak velocity is the mean of the maximum velocities of each fast-phase beat in the same direction, measured over the course of the test. The average frequency of the beats is calculated as the average of the inverse, of twice the beat duration. Specifically, each fast-phase beat is considered as one half of a sinusoidal cycle, and the duration of each fast-phase beat is found. The average number is the mean between tests of the number of beats in each direction.



Table 3. Summary of fast-phase analysis.

	VOR	OK	VVOR
Avg Amplitude	13.3±4.0	14.6±2.8	13.7±2.6
Avg Peak Velocity	274±61	337±64	286±48
Avg Frequency	5.36±0.84	5.93±0.82	5.52±0.91
Avg Number	99±26	119±19	137±21

Mean±standard deviation, Amp in deg, Vel in deg/sec

The Student's *t*-test for difference between means indicates that there is a significant difference in the average number of fast-phase beats between the tests, at  $p < 0.01$ . There is also a significant ( $p < 0.01$ ) difference in average peak velocity between OK and VOR and between OK and VVOR. All other characteristics are not significantly different when using different stimuli.

When the subject pool is divided into two groups, one under age thirty and the other over age thirty, no significant difference exists. However, two characteristics, average amplitude and average number of fast phases showed a significant difference, at  $p < 0.01$ , between men and women, as shown in Tables 4 and 5.

Table 4. Average amplitude, men vs. women.

Avg Amplitude	VOR	OK	VVOR
Men	11.5±1.6	13.7±2.4	12.4±1.6
Women	17.4±4.6	16.7±2.5	16.6±1.7

Table 5. Number of fast phases, men vs. women.

Avg Number	VOR	OK	VVOR
Men	110±23	129±11	149±14
Women	73±10	98±17	112±11

The results from the subject with the head injury are shown in Tables 6, 7, and 8. The slow-phase analysis shows a decreased gain and a large asymmetry to the left in the VOR. The OK and VVOR seem approximately normal. This indicates the head injury may have caused some trauma in the area of the left vestibular nuclei.

Abnormalities can also be identified by looking at the fast-phase analysis. All the ratios of right-beating versus left-beating fast phases are high for the VOR, showing a dominance to the right-beating movements. When comparing the individual characteristics to the normal group, all the left-beating statistics are low for the VOR. The OK responses tend to be higher than normal, especially for the right-beating movements. This indicates the body has attempted to compensate for the decreased vestibular movements by increasing the gain of the system. This increased gain is seen during visual only responses that have not been effected by the trauma. These conditions also indicate a possible problem in the area of the left vestibular nuclei.

Table 6. Head injury slow-phase response.

	VOR	OK	VVOR
Gain	.33	1.02	0.95
Phase	1.1	2.9	5.9
Asymmetry	-63.5	1.0	6.8

Phase in deg

Table 7. Head injury fast-phase right to left ratios.

Right/Left Ratio ....	VOR	OK	VVOR
Amplitude	1.69	1.17	0.96
Velocity	1.51	1.04	0.96
Number	2.51	0.82	0.89

Table 8. Head injury fast-phase analysis.

	VOR	OK	VVOR
Avg Amplitude - R	8.6	21.6	12.0
- L	5.1	18.4	12.6
Avg Peak Vel - R	241	461	316
- L	160	445	328
Avg Frequency	7.69	5.00	6.76
Avg Number - R	128	96	136
- L	51	117	153

Amp in deg, Vel in deg/sec

## Chapter Five: Discussion

This thesis is the first in-depth study of the characteristics of the fast-phase component of the nystagmus. Usually the fast movement of the eye is studied using the saccade test. Baloh, et al, has developed a saccade test that measures saccade amplitude, duration and velocity<sup>16</sup> and established a baseline using 25 normal subjects and four groups of patients.<sup>17</sup> They demonstrated that measuring a slowing in the saccade velocity can be used as a predictor of subclinical extraocular motor dysfunction.

Another research study used this work to evaluate the relationship between the fast-phase velocity and amplitude of per-rotary nystagmus resulting from constant angular rotary stimulation.<sup>18</sup> It was found that the uppermost point of nystagmus, in the velocity versus amplitude plot, tended to be larger in amplitude in cases with central vestibular disorders as compared to peripheral vestibular disorders.

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<sup>16</sup>Robert Baloh, Andrew Sills, Warren Kumley and Vicente Honrubia, "Quantitative measurement of saccade amplitude, duration and velocity", *Neurology* 25, (Nov 1975), 1065.

<sup>17</sup>Robert Baloh, Horst Konrad, Aandrew Sills, and Vicente Honrubia, "The saccade velocity test", *Neurology* 25, (Nov 1975), 1071.

<sup>18</sup>Yuji Imate, Toru Sekitani, Keiko Kanesada and Koji Hasuike, "Analysis of the Fast Phase of Per-Rotatory Nystagmus", *Acta Otolaryngol (Stockh)* (1991; Suppl. 481), 361.

Slow-phase and fast-phase velocities of the optokinetic nystagmus were studied by Yamada, et al.<sup>19</sup> They found that an impaired slow-phase velocity was a good indicator for infratentorial lesions, while an impaired fast-phase velocity indicated pontine lesions.

Katsarkas, et al,<sup>20</sup> looked at what role the fast phases of vestibular nystagmus played in gaze control. They found that the fast phases played an important role in the overall gaze control and concluded that the VOR should be redefined to include the contribution of the fast phases.

Since the fast-phase movement is so much quicker than the slow-phase movement, some questions have arisen as to whether the fast-phase is being correctly sampled. With the collection methods used in this thesis, each fast-phase beat has only 4 to 12 data points. There is some concern that some information is being lost, and the descriptions of the fast-phase movements are not accurate. More data points could be gathered by collecting data at greater than the 128 Hz sampling rate, but this is not very practical in the routine use of

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<sup>19</sup>Katsushi Yamada, Kimitaka Kaga and Nobuhiko Furuya, "Slow and Fast Phase Velocities of Optokinetic Nystagmus Induced by the Optokinetic Test in Infratentorial Lesions", *Acta Otolaryngol (Stockh)*, (1991; 111), 656.

<sup>20</sup>Athanasios Katsarkas, Henrietta Galiana, and Heather Smith, "Does the vestibulo-ocular reflex (VOR) merit redefinition?", *Otolaryngology - Head and Neck Surgery*, Vol. 105, Num 5, (November 1991), 633.

rotational testing because of the large amount of memory and storage that is required. Increasing the collection rate also would not make that much difference due to the 30 Hz bandwidth of the EOG system. Eye movements could be collected at a much greater bandwidth using an infrared sensor, but this creates other problems and is not very practical. The infrared sensors must be carefully positioned and remain in a fixed position relative to the head. Doing this during rotational testing would be very difficult and uncomfortable for the subject, who would have to wear a tight fitting, bulky pair of glasses. There would also be a lot more noise in the system. The collection method used in this thesis remains the most practical and widely used system. Fast-phase movements collected during these studies had frequencies between 5 and 6 Hz, which is well within the bandwidth of this system. As long as data is collected in a similar manner, it should be comparable to the results of this study.

In a study done by Longbotham, et al, for Brooks AFB<sup>21</sup>, it was suggested that the FIR median filter originally used by Brooks AFB may be changing the fast-phase data points. Since

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<sup>21</sup>H.G. Longbotham, et al, "Nonlinear Approaches for Separation of Slow and Fast Phase Nystagmus Signals", *Biomedical Sciences Instrumentation*, Vol 30, (April 1994).

each fast-phase movement has so few points, the predicted values for the fast-phase are biased by the slow-phase component. Currently a de-biased FIR median filter is being used. Longbotham suggested that the use of a robust differentiating filter and a WMMR filter would be a better way to separate slow- and fast-phase components without changing the original data points. Testing at Brooks AFB has shown that there is no significant difference in the slow-phase component between the WMMR filter and the AATM filter currently being used. An interesting future study would be to compare the fast-phase characteristics when using the different filtering methods to determine if the data is being changed by the FIR median filter.

## **Chapter Six: Conclusions**

Experiencing dizziness and nausea while trying to perform daily tasks is very frustrating. These symptoms can be signs of disorders in the vestibular system. Sinusoidal acceleration testing is becoming a common method of testing the vestibular system. By rotating a subject in the dark, a vestibular nystagmus can be elicited. An optokinetic nystagmus can be produced by using stripes rotating around the subject as a visual stimulation. These two stimuli can be combined to elicit a visual vestibulo-ocular response.

Nystagmus is composed of two movements: a slow-phase and a fast-phase. Currently only the performance of the slow-phase movement is routinely used to diagnose vestibular disorders. This thesis attempts to characterize the fast-phase movement by defining normal amplitudes, velocities, frequencies and number of beats during VOR, OK and VVOR testing.

Evaluating the fast-phase component of the VOR, OK, and VVOR can be added to the current rotational testing procedures very easily. In fact, test procedures do not have to be changed at all. An additional software module can evaluate data that is currently collected to obtain the fast-phase responses and find



their basic characteristics with minimal additional computational time. This could give additional diagnostic information with minimal effort.

Additional studies are needed before this information becomes diagnostically useful. More subjects that are known to have no abnormalities are needed to give a normal baseline. Further study on the difference between the responses of men and women should also be performed, to better understand where these differences originate. Patients with a wide range of known diseases or abnormalities must also be tested to determine how each condition affects the fast-phase response. This data base needs to be developed over time in a clinic that evaluates a wide range of patients and can follow up on diagnostic findings. This information may one day allow quicker and more complete diagnosis of the vestibular system.

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## **Vita**

Rebecca Brockway Schultz was born in Nuernbuerg, Germany, on August 23, 1966, the daughter of Wesley Arthur Brockway and Patricia Ann Brockway. In September, 1984, she entered Carnegie Mellon University. In May, 1988, she received a Bachelor of Science in Electrical Engineering and Biomedical Engineering from Carnegie Mellon Universtiy. In May 1988 she was commissioned into the United States Air Force. She was stationed for four years at Brooks, Air Force Base, San Antonio, Texas, where she worked as a Biomedical Engineer in the Crew Technology Division of the USAF School of Aerospace Medicine. In August, 1992 she entered The Graduate School of The University of Texas.

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